Polarization SAR system

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Abstract. A mathematical model is constructed for the dependence of the specific ESR on the slip angle for various types of X-band surfaces. A fully polarimetric radar image of a terrain site, synthesized from a three-dimensional model of the underlying surface.

Keywords: pseudo-color image, recognition, synthetic apperture radar.

1. Introduction

To simulate and analyze algorithms for the formation and processing of radar images, an important role is played by modeling the various stages in the process of obtaining a radar image. Modeling allows investigating in a wide range the influence of observation conditions, radar parameters, and used algorithms for the formation and processing of radar signals on the characteristics of the resulting image.

A promising method of increasing the informativeness of radar methods of research is the use of polarimetric data. Full polarization synthesized aperture radars (SAR) allow for each pixel of the radar image to obtain a scattering matrix in which all information about the polarimetric properties of the scattering of radio waves from the region under investigation is contained. Polarimetric information makes it possible to classify image objects according to the type of reflection in those cases when they have similar values of the specific Radar Cross Section (RCS). This classification finds its application both in the military and in the civilian industry.

2. Decomposition of the scattering matrix

There are several methods for the scattering matrix decomposition based on the representation of the scattering matrix as a linear combination of the matrices corresponding to the basic scattering mechanisms [1].

One such method is the representation of the scattering matrix as a sum of the Pauli matrices:

$$S = \frac{a}{\sqrt{2}}\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} + \frac{b}{\sqrt{2}}\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix} + \frac{c}{\sqrt{2}}\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix} + \frac{d}{\sqrt{2}}\begin{bmatrix}0 & -\mathrm{i}\\ \mathrm{i} & 0\end{bmatrix}. \quad (1)$$

The first term corresponds to the single scattering without change of polarization, the second term - corresponds to a double reflection in which one of the orthogonal components of the polarization changes sign. The third term represents the scattering-on dihedral reflector oriented at an angle of 45 degrees to the vertical. When reflected from such a reflector, the polarization of the wave changes to an orthogonal one. In the case of backscattering, the Pauli basis will include only the first three matrices.

Another form of representation of the scattering matrix is the Krogager decomposition. With this decomposition of the scattering matrix is represented as a sum of matrices corresponding to scattering from a sphere, dihedral corner reflector, and helix. For the last two reflectors, the matrices depend on the orientation angle θ of the reflector. The scattering matrix for this expansion is as follows:

$$S = k_\mathrm{s} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + k_\mathrm{d} \cdot \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix} + k_\mathrm{h} \cdot \mathrm{e}^{\mp \mathrm{i} 2\theta} \cdot \begin{bmatrix} 1 & \pm\mathrm{i} \\ \pm\mathrm{i} & 1 \end{bmatrix}. \tag{2}$$

The coefficients k_s, k_d, and k_h determine the contribution of the corresponding scattering mechanisms.

The decomposition of the scattering matrix system Pauli matrices and decomposition Krogager allow a visual assessment of the geometry and the degree of heterogeneity of the surface of natural and artificial objects.

Another group of methods is based on the analysis of coherence matrix T, the elements of which are calculated by transformations of scattering matrix S.

$$T = \frac{1}{2} \begin{bmatrix} (S_\mathrm{HH} + S_\mathrm{VV}) \cdot (S_\mathrm{HH} + S_\mathrm{VV})^* & (S_\mathrm{HH} + S_\mathrm{VV}) \cdot (S_\mathrm{HH} - S_\mathrm{VV})^* & 2(S_\mathrm{HH} + S_\mathrm{VV}) S_\mathrm{HV}^* \\ (S_\mathrm{HH} - S_\mathrm{VV}) \cdot (S_\mathrm{HH} + S_\mathrm{VV})^* & (S_\mathrm{HH} - S_\mathrm{VV}) \cdot (S_\mathrm{HH} - S_\mathrm{VV})^* & 2(S_\mathrm{HH} - S_\mathrm{VV}) S_\mathrm{HV}^* \\ 2S_\mathrm{HV}(S_\mathrm{HH} + S_\mathrm{VV})^* & 2S_\mathrm{HV}(S_\mathrm{HH} + S_\mathrm{VV})^* & 4S_\mathrm{HV} S_\mathrm{HV}^* \end{bmatrix}. \tag{3}$$

The coherence matrix has three positive eigenvalues λ_1, λ_2, λ_3. In [2] it was suggested to use the relation:

$$P_j = \frac{\lambda_j}{\lambda_1 + \lambda_2 + \lambda_3}, \quad j = 1, 2, 3; \tag{4}$$

with the use of which a parameter was introduced, called the scattering entropy

$$H = -\sum_{j=1}^{3} P_j \log_3 P_j. \tag{5}$$

Scattering entropy represents the degree of randomness of the scattering, its values lie between 0 and 1. The value $H = 0$ corresponds to the perfect single reflection mechanism, and the value $H = 1$ — complete diffuse scattering.

Coherence matrix can be reduced to diagonal form by transformation

$$T = U \cdot \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \cdot U^{-1}, \tag{6}$$

$$U = \begin{bmatrix} \cos\alpha_1 & \cos\alpha_2 & \cos\alpha_3 \\ \sin\alpha_1 \cos\beta_1 \exp(\mathrm{i}\delta_1) & \sin\alpha_2 \cos\beta_2 \exp(\mathrm{i}\delta_2) & \sin\alpha_3 \cos\beta_3 \exp(\mathrm{i}\delta_3) \\ \sin\alpha_1 \cos\beta_1 \exp(\mathrm{i}\gamma_1) & \sin\alpha_2 \cos\beta_2 \exp(\mathrm{i}\gamma_2) & \sin\alpha_3 \cos\beta_3 \exp(\mathrm{i}\gamma_3) \end{bmatrix} \tag{7}$$

Based on the matrix U, the average angle can be calculated

$$\alpha = \sum_{j=1}^{3} P_j \alpha_j, \tag{8}$$

which characterizes the dominant scattering mechanism. A value of $\alpha = 0^\circ$ corresponds to isotropic scattering on the surface, $\alpha = 45^\circ$ — dipole scattering, and the value $\alpha = 90^\circ$ — the double reflection.

Thus, methods of analyzing the coherence matrix allow us to divide natural objects into clusters with different scattering mechanisms.

3. Modeling of polarization SAR

In the simulation process of producing a radar image arises the problem of constructing electrodynamic and statistical models describing the main types of objects and the underlying surfaces.

To model the reflection of the signal from the surface, a polygonal surface model was used, representing the surface in the form of a set of elementary reflecting elements that are plates of finite dimensions that coincide with the surface of large-scale irregularities as presented at figure 1. In this case, the size of the facets should be less than the resolving power of the radar [3].

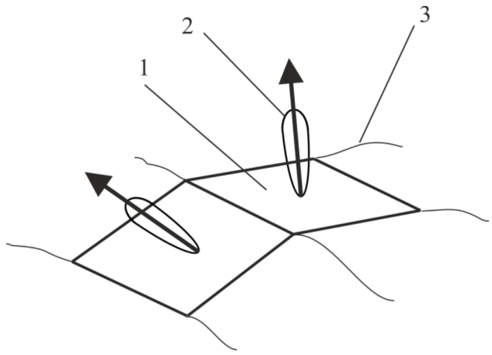

Figure 1. Faceted model of radar reflection by the earth's surface: 1 — facet; 2 — local backscattering diagram; 3 — surface.

The signal reflected from the surface is the sum of the signals from all the irradiated facets. The signal from each individual facet has its own amplitude determined by the orientation of the local backscattering diagram and its random phase.

To simulate the reflection of radio waves from different types of reflecting areas, a database of underlying surfaces was created. Important parameters of the underlying surfaces are the values of the specific RCS in different polarization channels and the phases of reflected electromagnetic waves in different polarizations

The exact solution of the problem of reflection of radio waves from rough surfaces causes serious mathematical difficulties. Therefore, we used an empirical model, such that the calculation of the reflected field was fairly simple, and the calculated parameters of the reflected waves were close to known experimental data.

When reflected from the earth's surface, the specific RCS value has a large range of changes and depends on the type of surface and the angle at which sensing occurs.

At angles close to the vertical sensing for most surfaces will be close to the mirror reflection and the highest values of specific RCS. At the angles close to the horizontal, the reflection will be very small. At intermediate values of the slip angle, the specific RCS, expressed in dB, varies with increasing slip angle according to a law close to linear.

Figures 2 shows the dependence of the specific RCS for backscattering on the sliding angle used for modeling the scattering of radio waves for different types of underlying surfaces with vertical, horizontal and cross polarization in the X-band. The model is based on the experimental data given in [4–6].

Experiments using polarimetric SAR given in [7], show that for a phase difference between reflected waves with matched polarization and cross-polarization has a uniform distribution in the interval $[0, 2\pi]$ for any distributed targets and, therefore, does not contain information about the target. In contrast, the phase difference of the reflected radio waves on the matched polarizations depends both on the wavelength and the angle of incidence, and on the parameters of the target, such as its shape and dimensions, surface roughness, and material properties.

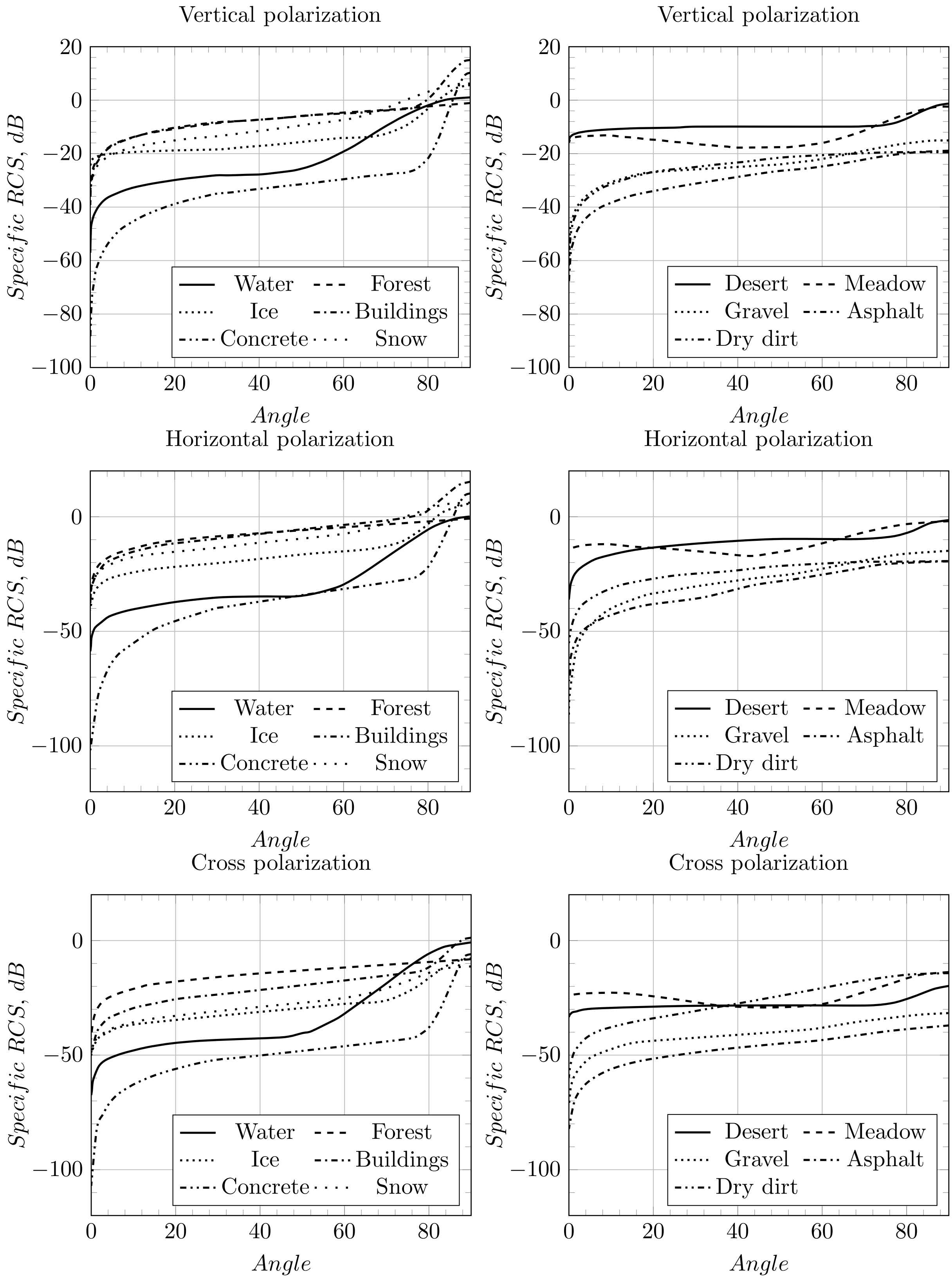

Figure 2. Dependence of specific RCS various surfaces of slip angle for different polarizations.

Upon reflection from the relatively smooth surfaces of the phase difference will be close to zero. In the case of double reflection, for example from buildings or tree trunks, the phase difference will be close to 180°. In scattering from an inhomogeneous medium, for example from vegetation, the phase difference can vary from 0 to 180°. In some cases, there may be joint effect of these scattering mechanisms.

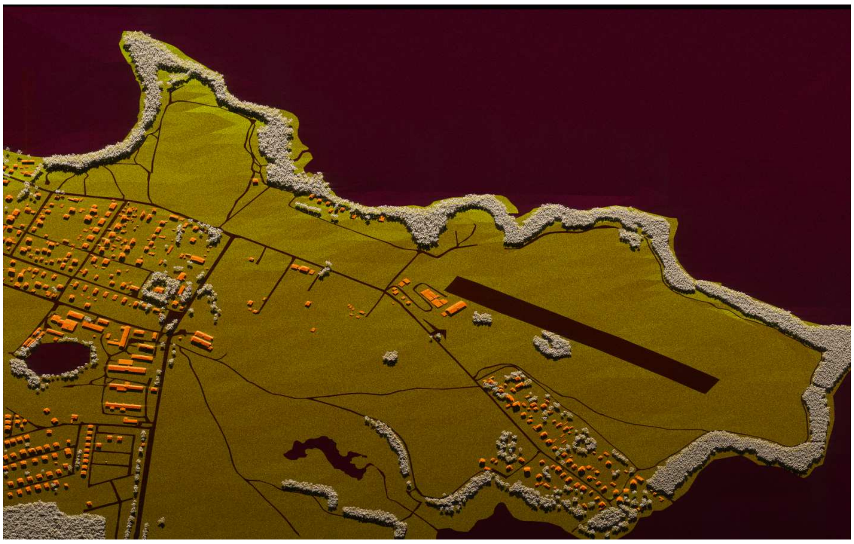

Figure 3. Radar image in cross polarization.

Using the created model of radar signal reflections were simulated process of producing a radar image. Results are shown in figure 3. Different material types have their own pseudo colors: grass — yellow-green; houses — orange; trees — white; water — dark purple. When generating radio holograms, the following model parameters were set:

- Flight altitude: 5 km;
- Flight path: linear;
- Resolution: 30 cm;
- Scanning angle: 45°;
- Modulation: phase;
- Carrier frequency: 10 GHz.

The simulated scene has the following dimensions: width 2700 m; length of 2500 m; height 40 m. The average height of the houses is one floor.

The differences between figure 3 and figure 4 are not so big, but they exist. The more obvious difference in comparison to figure 5 in which presented a cross polarization data. Three types of data can form a pseudo-color image, where different kinds of material presented in different colors. There are many ways to combinate that data, beginning from methods of equalization of color channels ending with subtraction channels in various combinations, it depends on the purpose of SAR.

4. Conclusions

The created model can be used to study algorithms for obtaining radar images, segmentation, and recognition of objects from their radar images, and to study the influence of observation conditions and various distorting factors on the resulting image.

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